Synopsis of the thesis entitled

Diversity and Coexistence of Nuclear Shapes at High Spins in ^{70}Ge and ^{73}As

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Atomic nuclei are complex many-body quantum ensembles composed of two kinds of particles namely protons and neutrons which are bound together with the strong nuclear forces. Protons and neutrons are fermions bounded in a small nuclear volume, which obey *Pauli* principle. The nuclear force exists between these fermions is very complex, and not an easy task to understand like other fundamental forces. The study of the nucleus presents many aspects which challenge our understanding the many-body problem of nuclear properties and their relationship to the underlying fundamental interactions. The study of properties of nuclear excited states can give information about the forces between these nucleons and the behavior of this many particle system.

Study of nuclear excited states at high angular momentum has been the subject of intense theoretical and experimental interest over past several years. This is primarily due to the unique possibility such studies offer new insights of nuclear structure and also provide test to theoretical predictions. Various aspects of nuclear structure can be revealed by studying the nuclei under extreme conditions such as moderate excitation energy, high angular momentum, large values of isospin and considerable amount of deformation. γ-ray spectroscopy is one of the most powerful tools to investigate nuclear structure. The study of static nuclear properties like mass, charge, binding energy, angular momentum and dynamic properties like quadrupole moments, transition probabilities would be helpful in describing the nuclear shape.

Systematic experimental studies have become feasible due to the improved technique of exciting high-spin states in nuclear reactions induced by accelerated heavy ions and with the availability of large volume high resolution HPGe detector arrays. The n-type coaxial High Purity Germanium (HPGe) detectors have been universally used for discrete γ-ray spectroscopy due to their good resolution compared to other detection media because the energy required to create an electron-hole pair in Ge is 3 eV, is less than as compared in the case of Si (100 eV). Thus an incident γ-ray with an energy of several hundred keV, produces a large number of such pairs, leading to good resolution and low statistical fluctuations.

The new generation of Ge γ-ray detector arrays having better energy resolution and total detection efficiency coupled with other ancillary devices have proved powerful ex-

perimental systems. These systems can be used to study nuclei populated with extremely low cross sections and the heavy ion fusion evaporation reaction is most commonly used for populating high spin states in the neutron-deficient nuclei.

The systematic study of nuclei at higher angular momentum with the use of heavy ion accelerators and with the improved spectroscopic techniques and methods, have revealed various new interesting phenomena along the nuclear chart such as Magnetic rotation, Chirality, Shape coexistence, Super deformation *etc.* The structural changes observed in rotational bands due to coupling of the collective and single-particle excitations with increasing rotational frequencies can give insight into the quantum mechanical states on which the rotation is imposed. Furthermore, the interplay between single-particle motion and collective degrees of freedom, pairing in atomic nuclei are seen as a rich tapestry of coexisting nuclear shapes and exotic excitations. The neutron deficient mass 70 region is one of such platform of nuclear chart privies ideal ground for coexistence of various nuclear shapes.

The basic objective of the present study is

1. To study the high spin structures of odd-A Arsenic isotope i.e.^{73}As (Z = 33, N = 40) and to search for the possibility of shape coexistence in it.

2. To study the spectroscopic properties of ^{70}Ge (Z = 32, N = 38) nucleus and shape evolution in it with increasing angular momentum.

Nuclear γ-spectroscopy at high-spins in the f-p-g shell nuclei around mass 70 region assume significance due to presence of rich verity of nuclear shapes in the same nucleus. Such shape coexistence is resulted from the complex interplay between single-particle and collective degrees of freedom and are the subject of interest in the present thesis. The total energy surface calculations for the nuclei in this region exhibit either more than one minimum with small barrier between them or they are gamma soft in nature. Thus the coexistence of prolate and oblate shapes at low-spins is to be understood and it would be interesting to see how these structures compete with each other at higher angular momentum.

High spin structure of several even-A nuclei have been studied in this region. The coexistence of overlapping bands built on different nuclear shapes and also the observation

of many low spin states, like 0^+ or 2^+ states, at very low excitation energy. These are related to the competition between various configurations at different deformations displayed by the Nilsson single particle energy diagrams. Whereas very limited studies were reported for odd-A nuclei. In particular the alignment systamatics of the $1g_{9/2}$ configurations in odd A-As and even-A Ge isotopes and the associated shape evolution in these isotopes shows several interesting nuclear phenomena. As an evidence of coexistence of spherical ground state band with the deformed first excited 0_2^+ band was reported in ^{70}Ge [1]

The Arsenic isotopes ^{67}As, ^{69}As, ^{71}As (Z= 33) [2, 3, 4] having one proton hole and few neutron particles with respective to the N = Z = 34 core. In recent studies oblate collectivity has been predicted in ^{67}As and this nucleus was more readily described in terms of the weak coupling of a $g_{9/2}$ proton to the ^{66}Ge core. In case of ^{69}As shape transition from an oblate at low spin to a prolate at high spin has been observed. This shape transition in ^{69}As has been interpreted is being due a two quasi neutron alignment. A similar trend has also been observed in ^{68}Ge [5], where as in the case of ^{71}As, moderate to high collectivity has been observed and the Total Routhian Surface(TRS) calculations predicts triaxiality in this nucleus at high spin. In this regard it is of interest to study ^{73}As nucleus to get wide knowledge of structural effects and shape evolution with increasing angular momentum.

The structure of the odd-A nucleus ^{73}As has been studied previously in late 70's by γ spectroscopic methods using (p, nγ),(α, 2n) reactions [6, 7] provided information on ground state spin, parity and few low-lying states. The positive parity yrast sequence on top of 428.2 keV $9/2^+$ isomer state was studied up to spin $25/2^+$ and excitation energy $\cong$ 4.1 MeV using heavy ion reactions ^{58}Fe(^{18}O, p2n) ^{73}As and ^{71}Ga(α, 2n) ^{73}As [8]. Several theoretical models were employed to describe the low spin states of this nucleus like particle+rotor model by Tucker [9, 10] and Ten Brink et al., [11] and Coriolis coupling model by B.Heits et al [8]. The results of the earlier experiments of ^{73}As confirms that the information about the non-yrast states are very limited. The study of these states would offer important evidence about the shapes involved at low excitation energies. Moreover the ground state band in this nucleus is known only up to $25/2^+$. Extension of this ground

state band above $25/2^+$ will give insight in to the stability of deformation of the ground state band at higher excitation energies.

The intriguing properties of the even-even germanium isotopes in mass 70 region have been studied in a number of previous experimental and theoretical works. These isotopes belongs to a typical transitional region stays between spherical and deformed regions regions of the nuclear chart are usually soft with respect to deformation changes. The structure of the low-lying states of these isotopes can be understand as arising from the interplay of rotational and vibrational collective motions. The doubly even germanium isotopes have been studied extensively because of the striking features of systematics of their low-lying states. ^{66}Ge, ^{68}Ge [5] were studied up to moderate spins, and discussed the role of $g_{9/2}$ orbital in them. Many theoretical attempts were made to describe the lighter Ge isotopes, each one concluded in a different way based on their assumptions. For example the study of $^{70-72}$Ge by Kumar [12] on the basis of dynamic deformation theory, predicted a weak transition from a spherical ^{70}Ge to an oblate ^{72}Ge shape. In contrast Parvaiz *et al.*,[13] reported prolate nature to these isotopes based on Projected Shell Model calculations. Moreover the shape calculations of these isotopes highly dependent of valance quasi-nucleons predicted varying shapes with increasing proton and neutron number. Hence the study of ^{70}Ge would offer more insight in to the structural effects and shape changing effects with increasing angular momentum. Therefore In the present work, we have chosen one odd-A nucleus ^{73}As and one even-even nucleus ^{70}Ge to study the structural changes in this region.

In this work, the nuclear excited states of ^{73}As and ^{70}Ge were populated using the fusion-evaporation reaction ^{64}Ni(^{12}C, p2n) ^{73}As and ^{64}Ni(^{12}C, α2n)^{70}Ge. Beam of ^{12}C ions with energy 55 MeV and beam current of 1pnA was provided by Pelletron accelerator [14] at IUAC, New Delhi. The target used was 1.5mg/cm^2 thickness with 7mg/cm^2 Au backing. The de-excited γ rays from residual nuclei were detected with Gamma Detector Array (GDA) facility [15] contains 12 Compton suppressed n-type Hyper Pure Germanium (HPGe) detectors, separated in to three groups each consisting of four detectors and are mounted co-axially in Anti-Compton Shields making an angle 45°, 99°, 153° with respective to the beam direction and are tilted ±23° with respect to the

horizontal plane.

The online CAMAC based data acquisition system CANDLE [16] was used to record $\gamma - \gamma$ coincidences by event-by-event. A total of more than 130 million two and higher fold events were recorded in list mode. [16]. The offline data analysis were done using the analysis programs CANDLE [16], INGASORT [17], and RADWARE [18]. The list mode data were sorted into a two dimensional 4k $\times$ 4k total $E_\gamma - E_\gamma$ matrix from which the coincidence spectra were generated using the program INGASORT with a dispersion of 0.5 keV/channel and it covers the energy range $\approx$ 30 keV to 2 MeV. This was the primary matrix set used for the construction of the level scheme. In addition, a separate 4k X 4k angle dependent matrix was constructed by taking energies of the γ-transitions from all of the detector at forward (45°) or backward (153°) angle on one axis and the coincidence γ-energies from all of the detectors at $\approx$ 90° on the other axis. This angle dependent matrix set was used to assign the multipolarity of the γ-transitions using conventional Directional Correlation Orientation(DCO) technique [19]. The experimental DCO ratio for this present work is defined as the ratio of the intensity(I) of measured transitions observed at 45° or 153° with gates on reference γ rays at 99° to the intensity of measured transitions at 99° with gates on reference γ-rays at 45° or 153°(where the reference γ-ray is of known multipolarity).

In the present work, the level scheme of ^{73}As has been extended to a spin of J = $37/2\hbar$ and an excitation energy of 8.7 MeV with the addition of 30 new transitions to the previous work [20]. The preliminary results of this work are reported in Ref [21, 22]. The experimentally observed rotational band structures in both positive and negative parity are compared with the predictions of triaxail Particle plus Rotor Model(PRM). The results of these calculations reproduces very well the properties of yrast states in ^{73}As such as excitation energies, signature splitting and branching ratios. The positive parity bands is likely built on the local minimum with configuration $\pi 1g_{9/2}$ of a triaxially deformed shape, while the negative parity one on the global minimum with valence proton configuration $\pi(2p_{3/2}1f_{5/2}2p_{1/2})^5$ of an oblate shape. The shape evolution related to the different configuration mixing with increasing angular momentum is explained in the light of Cranked shell model (CSM) and the Total Routhian Surface (TRS) calculations. The

TRS for the positive and negative parity bands indicate a triaxial prolate-oblate shape coexistence at low rotational frequency, which is further supported by the PRM results too.

The second nucleus ^{70}Ge has been studied in the same experiment and the level scheme has been extended up to $J^{\pi} = (19^{-})$ and excitation energy of $\cong$ 11.06 MeV with the addition of several transitions. The preliminary results of this work are reported in Ref [23]. A new positive parity side band built on $g_{9/2}$ zero-quasi particle ground state band becomes yrast at high spins which has been interpreted as being due to the alignment of a pair of $g_{9/2}$ neutrons. The experimentally observed band structures are discussed in the light of Cranked Shell Model (CSM) calculations and their experimental crossing frequencies are well in agreement with the quasi-particle routhians calculated using Nilson-strutinsky formalism. The Total Routhian Surface (TRS) calculations has been carried out which confirm that this nucleus shows great deal of γ softness at low spins ($\hbar\omega$ = 0) changes to a triaxial prolate at intermediate spins ($\hbar\omega \sim$ 0.5-0.7 MeV). The present work established substantially new information on the high spins states in both ^{73}As and ^{70}Ge. The alignment properties and shape competition between different configurations have been discussed in the light of PRM and CSM calculations. The calculations were found to reproduce consistent results in this vibrational-rotational transitional region. The measurements of transition probabilities and life time of the excited states of these nuclei would be helpful in extending our knowledge about the structure of these nuclei and can be considered in future experiments.

The present thesis is organized in total 6 Chapters. General introduction to the subject of the thesis, motivation and plan of the thesis is are explained in **Chapter 1**. The salient features of the various theoretical nuclear models, which are used to interpret the experimentally established level structures are presented in **Chapter 2**. In **Chapter 3**, the experimental techniques and data analysis procedure are explained at length. **Chapter 4** presents the introduction about the nucleus under study, motivation, details of the previous structure studies of ^{73}As at low and high spins. Thereafter we have discussed the procedure in studying ^{73}As, data analysis methods and the results obtained in the experiment. Finally we have discussed the interpretation of the experimental results with

the Particle rotor model (PRM) and Cranking Model Calculation in detail. In **Chapter 5**, the details of investigation of nuclear structure of ^{70}Ge are given. Experimental procedure and various data analysis methods in getting the nuclear structure information of ^{70}Ge are explained. The details of the obtained results and their interpretation with the Cranking shell model (CSM) calculations have been discussed in depth. **Chapter 6** contains a summary of the total work carried out in this thesis and conclusions.

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